UNITED STATES PATENT APPLICATION

FOR

METHOD AND APPARATUS FOR TUNING A BRAGG GRATING IN A SEMICONDUCTOR SUBSTRATE

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BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to optical devices and, more specifically, the present invention relates to Bragg grating optical devices.

Background Information

The need for fast and efficient optical-based technologies is increasing as Internet data traffic growth rate is overtaking voice traffic pushing the need for optical communications. Commonly used optical components include diffraction gratings, thin-film filters, fiber Bragg gratings, and arrayed-waveguide gratings.

A fiber Bragg grating is an optical fiber device that includes an optical fiber with periodic changes in the refractive index of fiber core materials along the fiber length, which may be formed by exposure of the photosensitive core to an intense optical interference pattern. With the changes in the refractive index along the fiber length, optical beams at a particular wavelength are reflected by the fiber Bragg grating while other wavelengths are allowed to propagate through the fiber.

A limitation with known fiber Bragg gratings is that the particular wavelength that is reflected by the fiber Bragg grating is substantially fixed. Consequently, if different wavelengths of light are to be reflected, different fiber Bragg gratings are utilized. In some known fiber Bragg gratings, nominal adjustments to the reflected wavelength may be provided by physically or mechanically stretching the optical fiber of the fiber Bragg grating to modify the length of the optical fiber. The disadvantage of this technique is that the amount of adjustment to the reflected wavelength is relatively small and the optical fiber may

suffer damage from the physical stress and strain of the stretching.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example and not limitation in the accompanying figures.

Figure 1 is a block diagram illustrating a cross section of one embodiment of a tunable Bragg grating disposed in a semiconductor substrate including a heater in accordance with the teachings of the present invention.

Figure 2 is a perspective diagram illustrating one embodiment of a tunable Bragg grating disposed in a semiconductor substrate including a rib waveguide disposed in a semiconductor substrate in accordance with the teachings of the present invention.

Figure 3 is a diagram illustrating the relationship between reflectivity and wavelength at different temperatures of one embodiment of a tunable Bragg grating in accordance with the teachings of the present invention.

Figure 4A is a diagram illustrating the effective index of refraction along an optical path of one embodiment of a tunable uniform Bragg grating in accordance with the teachings of the present invention.

Figure 4B is a diagram illustrating the effective index of refraction along an optical path of one embodiment of a tunable apodized Bragg grating in accordance with the teachings of the present invention.

Figure 5 is a block diagram illustrating a cross section of another embodiment of a tunable Bragg grating disposed in a semiconductor substrate including charge modulated regions in accordance with the teachings of the present invention.

DETAILED DESCRIPTION

Methods and apparatuses for tuning a Bragg grating disposed in a semiconductor substrate are disclosed. In the following description numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one having ordinary skill in the art that the specific detail need not be employed to practice the present invention. In other instances, well-known materials or methods have not been described in detail in order to avoid obscuring the present invention.

Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

In one embodiment of the present invention, a semiconductor-based tunable Bragg grating is provided in a fully integrated solution on a single integrated circuit chip. In one embodiment, an infrared or near infrared input optical beam is selectively reflected at a tunable center wavelength with a silicon-based optical grating or filter in accordance with the teachings of the present invention. As will be discussed, the reflected wavelength bandwidth is relatively narrow. The center wavelength is shifted using various techniques including thermal or plasma optical effects in for example silicon. Embodiments of the presently described semiconductor-based tunable Bragg grating may be utilized in broadband optical networking systems or the like.

To illustrate, Figure 1 is a block diagram illustrating a cross section of one

embodiment of a semiconductor-based tunable Bragg grating 101 disposed in a semiconductor substrate 103 in accordance with the teachings of the present invention. In the depicted embodiment, Bragg grating 101 is silicon/polysilicon grating. It is appreciated that silicon and polysilicon are example materials provided for explanation purposes and that other semiconductor materials including III-V semiconductor materials or the like may be utilized in accordance with the teachings of the present invention. As shown, a plurality of regions of polysilicon 105 are disposed in a silicon semiconductor substrate 103 such that periodic or quasi-periodic perturbations in an effective index of refraction n_{eff} are provided along an optical path 117 through semiconductor substrate 103.

In one embodiment in which silicon and polysilicon are utilized, having effective refractive indexes of n_{Si} and n_{poly}, respectively, a small effective refractive index difference Δn_{eff} (or $n_{poly} - n_{Si}$) is provided at each interface between semiconductor substrate 103 and polysilicon 105. In one embodiment, Δn_{eff} is approximately within the range of 0.005 to 0.01. It is appreciated that other value ranges for Δn_{eff} may be utilized in accordance with the teachings of the present invention and that 0.005 to 0.01 is provided herewith for explanation purposes.

As illustrated in Figure 1, semiconductor substrate 103 is included in one embodiment in a silicon-on-insulator (SOI) wafer 115. As such, an insulating layer 107 or a buried oxide layer is disposed between semiconductor substrate 103 layer and another semiconductor substrate layer 113. In one embodiment, an additional insulating layer 109 is included such that semiconductor substrate 103 layer is disposed between insulating layers 107 and 109. In one embodiment, insulating layer 109 includes an interlayer dielectric layer of the SOI wafer 115. In one embodiment, insulating layers 107 and 109 include an oxide

material or the like. As a result, a waveguide 125 including optical path 117 is provided in semiconductor substrate 103 with cladding provided by insulating layers 107 and 109.

In one embodiment, waveguide 125 is a rib waveguide. To illustrate, Figure 2 is a perspective view illustration of one embodiment of a rib waveguide 225 of a tunable Bragg grating in accordance with the teachings of the present invention. In one embodiment, rib waveguide 225 is disposed between insulating regions 107 and 109 of SOI wafer 115 of Figure 1.

Referring back to Figure 2, rib waveguide 225 is disposed in a semiconductor substrate 203 and includes regions of polysilicon 205. In one embodiment, the semiconductor substrate 203 has a different index of refraction than polysilicon 205 such that periodic or quasi-periodic perturbations in an effective index of refraction are provided along an optical path through rib waveguide 225.

As shown, the rib waveguide 225 includes a rib region 227 and a slab region 229. In the embodiment illustrated in Figure 2, the intensity distribution of a single mode optical beam 219 is shown propagating through the rib waveguide 225. As shown, the intensity distribution of optical beam 219 is such that of the majority of the optical beam 219 propagates through a portion of rib region 227 towards the interior of the rib waveguide 225. In addition, a portion of optical beam 219 propagates through a portion of slab region 229 towards the interior of the rib waveguide 225. As also shown with the intensity distribution of optical beam 219, the intensity of the propagating optical mode of beam 219 is vanishingly small at the "upper corners" of rib region 227 as well as the "sides" of slab region 229.

Referring back to the illustration in Figure 1, an optical beam 119 is directed along optical path 117 into one end of waveguide 125. In one embodiment, optical beam 119 includes infrared or near infrared light and is confined with cladding provided by insulating

layers 107 and 109 to remain within waveguide 125 along optical path 117 between the ends of waveguide 125. In one embodiment, optical beam 119 is confined as a result of total internal reflection since the oxide material of insulating layers 107 and 109 has a smaller index of refraction than the semiconductor material of semiconductor substrate 103 and polysilicon 105.

In one embodiment, optical beam 119 includes a plurality of wavelengths including for example λ_1, λ_2 and λ_3. It is appreciated that although optical beam 119 has been illustrated to include three wavelengths λ_1, λ_2 and λ_3 in the illustrated example, a different number of wavelengths may be included in optical beam 119 in accordance with the teachings of the present invention.

As mentioned above, there are periodic or quasi-periodic perturbations in the effective index of refraction along optical path 117 through waveguide 125. As a result of the effective refractive index difference Δn_{eff} described above, a multiple reflection of optical beam 119 occurs at the interfaces between semiconductor substrate 103 and polysilicon 105 along optical path 117. In one embodiment, a Bragg reflection occurs when a Bragg condition or phase matching condition is satisfied. In particular, for uniform Bragg gratings, when the condition

$$m\lambda_B = 2n_{eff}\Lambda, \qquad \text{(Equation 1)}$$

is satisfied, where m is the diffraction order, λ_B is the Bragg wavelength, n_{eff} is the effective index of the waveguide and Λ is the period of the grating, a Bragg reflection occurs.

To illustrate, Figure 1 shows a Bragg condition existing for λ_B equal to λ_2. Accordingly, an optical beam 121 including wavelength λ_2 is shown to be reflected back out of the waveguide 125 out from the end into which optical beam 119 is directed. In addition,

the remainder of optical beam 119 continues to propagate along optical path 117 through waveguide 125 such that the remaining wavelengths (e.g. λ_1 and λ_3) are included the an optical beam 123, which is propagated from the opposite end of waveguide 125. Accordingly, the Bragg wavelength λ_2 is filtered from optical beam 123. In one embodiment, optical beam 119 may be an optical communications beam or the like on which data is encoded. In one embodiment, wave division multiplexing (WDM) or dense wave division multiplexing (DWDM) or the like may be employed with optical beam 119 such that a different channel is encoded with each of the wavelengths (e.g. λ_1,λ_2, λ_3, etc.) included in optical beam 119.

In one embodiment, the Bragg wavelength, λ_B, that is reflected or filtered by tunable Bragg grating 101 is tunable or adjustable with a heater 111 disposed proximate to waveguide 125. In an embodiment, heater 111 includes a thin-film heater or the like or other future arising technology that controls the temperature of semiconductor substrate 103 and polysilicon 105 in waveguide 125 along optical path 117. For instance, silicon and polysilicon have large index of refraction variations with temperature on the order of approximately 2 x 10^{-4}/°K. It is appreciated that the index of refraction variations with temperature for semiconductor materials such as silicon and/or polysilicon are two orders of magnitude greater than other materials such as for example silica or the like. Thus, by controlling the temperature of semiconductor substrate 103 and polysilicon 105, relatively significant shifts in the center wavelength of light reflected by a tunable Bragg grating 101 are provided in accordance with the teachings of the present invention.

To illustrate, Figure 3 is a diagram 301 illustrating the relationship between reflectivity and wavelength at different temperatures of one embodiment of a tunable Bragg

grating 101 in accordance with the teachings of the present invention. In the illustrated example, heater 111 is used to adjust the temperature of silicon/polysilicon waveguide Bragg grating to 25°C, 75°C and 125°C. In the illustrated embodiment, the difference in the effective indexes of refraction between the silicon and polysilicon Δn_{eff} is approximately 0.008 and the period of the grating Λ is approximately 2 μm.

Plot 303 shows that at 25°C, the center wavelength of an optical beam that is reflected by the silicon/polysilicon waveguide Bragg grating is approximately 1.544 μm in the illustrated embodiment. In comparison, plot 305 shows that at 75°C, the center wavelength of an optical beam that is reflected is shifted or tuned to be approximately 1.548 μm, while plot 307 shows that at 125°C, the center wavelength of an optical beam that is reflected is shifted or tuned to be approximately 1.552 μm. In one embodiment, a thin-film heater utilized for heater 111 provides center wavelength tuning speeds in the order of microseconds

It is appreciated of course that the materials, dimensions, wavelengths and index of refraction values utilized in the embodiment illustrated in Figure 3 are provided for explanation purposes and that other materials, dimensions, wavelengths and index of refraction values may be utilized in accordance with the teachings of the present invention.

In one embodiment, there are sidelobes on the sides of each maxima of plots 303, 305 and 307. When uniform or periodic Bragg gratings are utilized, the sidelobes are usually relatively large. An example of a uniform grating with periodic perturbations in the effective index of refraction along the optical path of the Bragg grating is illustrated in diagram 401 in Figure 4A. As shown along the y-axis, the effective index of refraction n_{eff} is perturbed periodically or regularly down the optical path, which shown as Z along the x-axis of diagram 401.

In one embodiment, an apodized Bragg grating is provided in accordance with the teachings of the present invention, which reduces the sidelobes on the sides of each maxima of plots 303, 305 and 307. One embodiment of an apodized grating utilized in accordance with the teachings of the present invention is illustrated in diagram 451 of Figure 4B. An apodized grating is provided with quasi-periodic perturbations in the effective index of refraction along the optical path of the Bragg grating. The perturbation in the effective index of refraction can be realized by either changing refractive index of constitutive materials or varying layer widths (duty cycle) along the Bragg grating. It is noted that an embodiment of a raised-cosine apodized grating is illustrated in diagram 451 of Figure 4B. It is appreciated that other types of apodized gratings may be utilized in accordance with the teachings of the present invention including but not limited to Gaussian-apodized, chirped, discrete phase shift, superstructure or the like.

Figure 5 is a block diagram illustrating a cross section of another embodiment of a tunable Bragg grating 501 in accordance with the teachings of the present invention. As shown in the depicted embodiment, tunable Bragg grating 501 includes a semiconductor substrate 503 having an optical path 517 through which an optical beam 519 is directed. In one embodiment, semiconductor substrate 503 is included in an SOI wafer 515 such that semiconductor substrate is disposed between a buried insulating layer 507 and insulating layer 509. In addition, buried insulating layer 507 is disposed between semiconductor substrate layer 503 and semiconductor substrate layer 513. In one embodiment, an optical waveguide 525 is provided with semiconductor substrate 503 with insulating layers 507 and 509 serving as cladding to confine optical beam 519 to remain within waveguide 525 between the ends.

In the embodiment depicted in Figure 5, tunable Bragg grating 501 is provided with

trenched silicon structures. In particular, a plurality of conductor-insulator-semiconductor structures 515, similar to for example metal-oxide-semiconductor (MOS) structures, are disposed along optical path 517 in semiconductor substrate 503. Each structure 515 is coupled to receive a modulation signal V_G 539 through conductor 537, which is coupled to each structure 515 through insulating layer 509. As shown in Figure 5, the height of each structure 515 in waveguide 525 is h. In one embodiment, the height h of the structures 515 is chosen such that propagation loss of optical beam 517 in waveguide 525 along optical path 517 is acceptable.

In the embodiment depicted in Figure 5, periodic or quasi-periodic perturbations in an effective index n_{eff} of refraction are provided along an optical path 517 through waveguide 525 in semiconductor substrate 503. In particular, the effective index of refraction n_{eff} is related or equal to a function of the geometry of waveguide 525 along optical path 517 as well as the index of refraction of the specific medium (e.g. n_{Si}) and the wavelength λ included in optical beam 519.

Accordingly, assuming semiconductor substrate 503 includes silicon, the effective index of refraction n_{eff} is a function of the height H of waveguide 525 not including structures 515, n_{Si} and λ. In the regions 505 of waveguide 525 including structures 515, the effective index of refraction n'_{eff} is a function of the height (H - h) of waveguide 525 including structures 515, n_{Si} and λ. Thus, the difference in effective index of refraction

$$\Delta n_{eff} = n_{eff} - n'_{eff}. \qquad \text{(Equation 2)}$$

In the depicted embodiment, structures 515 are biased in response to modulation signal V_G 539 through conductor 537 such that the concentration of free charge carriers in charge modulated regions 531 in the semiconductor substrate layer 503 proximate to the structures 515. For example, assuming a positive voltage is applied with modulation signal

V_G 539 through conductor 537, electrons in semiconductor substrate 503 are swept into charge modulated regions 531. When for example less positive voltage is applied to conductor 537, the concentration of free charge carriers swept into charge modulated regions 531 is reduced.

It is noted that for explanation purposes, charge modulated regions 531 have been illustrated to include negative charge. It is appreciated that in another embodiment, the polarities of these charges and the voltages of modulation signal V_G 539 may be reversed in accordance with the teachings of the present invention.

In one embodiment, the effective index of refraction n_{eff} in charge modulated regions 531 is modulated in response to the modulation signal V_G 539 due to the plasma optical effect. The plasma optical effect arises due to an interaction between the optical electric field vector and free charge carriers that may be present along the optical path 517 of the optical beam 519. The electric field of the optical beam 519 polarizes the free charge carriers and this effectively perturbs the local dielectric constant of the medium. This in turn leads to a perturbation of the propagation velocity of the optical wave and hence the refractive index for the light, since the refractive index is simply the ratio of the speed of the light in vacuum to that in the medium. The free charge carriers are accelerated by the field and also lead to absorption of the optical field as optical energy is used up. Generally the refractive index perturbation is a complex number with the real part being that part which causes the velocity change and the imaginary part being related to the free charge carrier absorption. In the case of the plasma optical effect in silicon, the effective change in the index of refraction Δn_{eff} due to the free electron (ΔN_e) and hole (ΔN_h) concentration change is given by:

$$\Delta n_{eff} = -\frac{e^2 \lambda^2}{8\pi^2 c^2 \varepsilon_0 n_0}\left(\frac{\Delta N_e}{m_e^*} + \frac{\Delta N_h}{m_h^*}\right) \qquad \text{(Equation 3)}$$

where n_0 is the nominal index of refraction for silicon, e is the electronic charge, c is the speed of light, ε_0 is the permittivity of free space, m_e^* and m_h^* are the electron and hole effective masses, respectively.

It is noted that tunable Bragg grating 501 has been illustrated in Figure 5 with five structures 515. It is appreciated that in other embodiments, tunable Bragg grating 501 may include a greater or fewer number of structures 515 in accordance with the teachings of the present invention.

In operation, optical beam 519 is directed along optical path 517 into one end of waveguide 525. In one embodiment, optical beam 519 includes infrared or near infrared light and is confined with insulating layers 507 and 509 to remain within waveguide 525 along optical path 517 between the ends of waveguide 525. In one embodiment, optical beam 519 is confined as a result of total internal reflection since the oxide material of insulating layers 507 and 509 has a smaller index of refraction than the semiconductor material of semiconductor substrate 503.

In one embodiment, optical beam 519 includes a plurality of wavelengths including for example λ_1, λ_2 and λ_3. As a result of the effective refractive index difference Δn_{eff} described above in the periodic or quasi-periodic perturbations in the effective index of refraction along optical path 517, a multiple reflection of optical beam 519 occurs when a Bragg condition or phase matching condition is satisfied, as described above in Equation 1.

To illustrate, Figure 5 shows a Bragg condition existing for λ_B equal to λ_2. Accordingly, an optical beam 521 having a center wavelength λ_2 is shown to be reflected back out of the waveguide 525 out from the end into which optical beam 519 is directed. In addition, the remainder of optical beam 519 continues to propagate along optical path 517

through waveguide 525 such that the remaining wavelengths (e.g. λ_1 and λ_3) are included the an optical beam 523, which is propagated from the opposite end of waveguide 525. Accordingly, the Bragg wavelength λ_2 is filtered from optical beam 523.

In one embodiment, the center wavelength that is reflected or filtered by tunable Bragg grating 501 is tunable or adjustable by appropriately modulating charge in modulated charge regions 531 with modulation signal V_G 539 to adjust the conditions for the Bragg wavelength λ_B. Indeed, as discussed above, the difference in effective refractive index Δn_{eff} along optical path 517 is modulated in response to modulation signal V_G 539 to tune the Bragg wavelength λ_B that is reflected or filtered by tunable Bragg grating 501 in accordance with the teachings of the present invention.

In the foregoing detailed description, the method and apparatus of the present invention have been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the present invention. The present specification and figures are accordingly to be regarded as illustrative rather than restrictive.